Low-contrast and low-counting-rate measurements in neutron interferometry

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Here we discuss the limits of the recognizability of neutron interference patterns either observed in low-contrast measurements or when collecting very few neutrons only. Low contrast can be caused by a strong beam attenuation or by a large phase shift applied to one beam path. Stochastic and deterministic cases have different influences on the interference pattern, which can be interpreted as a different wavelike or particle-like behavior of the system. Measurements of interference patterns with very few neutrons only are related to the phase—particle-number uncertainty relation, which is discussed on the basis of stochastic and quantum theory arguments. Analogies between coherent-state behavior known in atomic physics and the behavior of neutrons in an interferometer are discussed also.

I. INTRODUCTION

Neutron interferometry has been developed for thermal, cold, and ultracold neutrons. Since its invention it has been used for many fundamental investigations concerning the wave-particle duality and the gravitational, electromagnetic, and strong interaction of the neutron with its surroundings. Neutrons are massive particles with many well-defined particle properties including an internal quark structure, but they behave in neutron interferometry like waves according to the complementarity principle of quantum mechanics. All the performed experiments belong to the regime of self-interference because the phase-space density of any neutron beam is extremely low (10^-14) and in nearly every case when a neutron passes through the interferometer the next neutron is still in a uranium nucleus of the reactor fuel. Therefore, in general, one observes, first-order interference fringes that are caused by a variable phase difference \( \phi \) of two overlapping coherent beams. The degree of coherence is defined as the absolute value of the autocorrelation function of the overlapping beams, which can be determined experimentally from the visibility of the interference fringes:

\[
I \propto 1 + \left| \langle \Gamma(\Delta) \rangle / \langle \Gamma(0) \rangle \right| \cos \phi
\]

with

\[
\Gamma(\Delta) = \langle \psi^*(0) \psi(\Delta) \rangle,
\]

where \( \Delta \) is the optical path difference and \( \phi \) the phase difference of the interfering beams \( \phi = k \cdot \Delta \).

A reduction of the visibility can be caused by a nonuniform phase shift across the beam, by a spatial shift of one wave train relative to the other in the order of the coherence lengths of the beam, or by the attenuation of one of the interfering beams. Most interference experiments aim high visibility at high counting rates in order to determine the phase difference as accurately as possible. Contrary to those experiments we are here dealing in the first part with experiments that show a low contrast and in the second part with such ones of very low counting rates. Both kinds are related to the question of the statistical and physical significance of an interference pattern and treat the limiting cases where interference phenomena can still be detected.

II. CONTRAST REDUCTION

BY BEAM ATTENUATION

The simplest way for beam attenuation is by inserting an absorbing material into one of the coherent beams of an interferometer. The absorption process can be described by an imaginary part of the index of refraction, yielding a complex phase shift

\[
\phi = \phi' + i \phi'', \quad (2)
\]

with \( \phi' = -N b_c \lambda D \) and \( \phi'' = N \sigma_t D / 2 \), where \( D \) is the thickness of the sample along the beam path, \( N \) is the particle density, \( b_c \) is the coherent scattering length of the sample, \( \lambda \) is the wavelength of the neutrons, and \( \sigma_t = \sigma_s + \sigma_g \) is the total cross section including absorption and scattering effects in order to fulfill the optical theorem of general diffraction theory. In the absorption process of a neutron a compound nucleus is formed with an excitation energy of about 7 MeV, which decays by \( \alpha \), \( \beta \), or \( \gamma \) radiation, which can be registered by various detectors. Absorption is an irreversible process caused by the statistical formation of the compound nucleus and can be seen as the essential step for a measuring process and indeed any absorbed neutron causes a signal identifying the beam path the neutron has chosen. The residual interference pattern reads as:

\[
I = I^0(a \epsilon_1 + \epsilon_2) + \frac{I'}{2} \left[ (a + 1) + 2 \sqrt{a} \cos \phi' \right], \quad (3)
\]